AFRL-RZ-WP-TP-2008-2034

EFFECTS OF CORONA, SPARK AND SURFACE DISCHARGES ON IGNITION DELAY AND DEFLAGRATION-TO-DETONATION TIMES IN PULSED DETONATION ENGINES (POSTPRINT)

Kenneth Busby, Jennifer Corrigan, Sheng-Tao Yu, Skip Williams, Campbell D. Carter, Frederick Schauer, John Hoke, Charles Cathey, and Martin Gundersen

Propulsion Sciences Branch
Aerospace Propulsion Division

DECEMBER 2006

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AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
December 2006

2. REPORT TYPE
Conference Paper Postprint

3. DATES COVERED *(From - To)*
30 April 2004 – 01 December 2006

4. TITLE AND SUBTITLE
EFFECTS OF CORONA, SPARK AND SURFACE DISCHARGES ON IGNITION DELAY AND DEFLAGRATION-TO-DETONATION TIMES IN PULSED DETONATION ENGINES (POSTPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
61102F

5d. PROJECT NUMBER
2308

5e. TASK NUMBER
AI

5f. WORK UNIT NUMBER
2308AI00

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8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RZ-WP-TP-2008-2034

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RZAS

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RZ-WP-TP-2008-2034

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference paper published in the Proceedings of the 45th AIAA Aerospace Sciences Meeting and Exhibit.
 Technical paper contains color.
PAO Case Number: AFRL/WS 06-2875, 19 Dec. 2006.

14. ABSTRACT
The purpose of the research described herein is to compare the ignition delays in an experimental pulsed detonation engine produced by thermal and non-thermal ignitions. The commercial thermal ignition has a pulse duration of about 1 μs, whereas the non-thermal ignitions have pulse durations of 100 ns. Ignition delay is an important factor, along with fill and purge times, that limit the maximum repetition rate and thrust of pulsed detonation engines. For stoichiometric fuel-air mixtures with aviation gasoline at 1 atmosphere and 360 - 480 K, an ignition delay of 6 ms was observed with a non-thermal ignition, whereas the ignition delay was 11 ms with an aftermarket automotive ignition. By replacing the resistive cable and resistor of the aftermarket ignition with a non-resistive cable and surface discharge igniter, its ignition delay was reduced to 7 ms, which is comparable to that produced by the non-thermal ignitions.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Campbell D. Carter
Unclassified	Unclassified	Unclassified	SAR	16	19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

45th AIAA Aerospace Sciences Meeting and Exhibit
8 - 11 January 2007, Reno, Nevada

AIAA 2007-1028

Effects of Corona, Spark and Surface Discharges on Ignition Delay and Deflagration-to-Detonation Times in Pulsed Detonation Engines

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The purpose of the research described herein is to compare the ignition delays in an experimental pulsed detonation engine produced by thermal and non-thermal ignitions. The commercial thermal ignition has a pulse duration of about 1 μs, whereas the non-thermal ignitions have pulse durations of 100 ns. Ignition delay is an important factor, along with fill and purge times, that limit the maximum repetition rate and thrust of pulsed detonation engines. For stoichiometric fuel-air mixtures with aviation gasoline at 1 atmosphere and 360-480 K, an ignition delay of 6 ms was observed with a non-thermal ignition, whereas the ignition delay was 11 ms with an aftermarket automotive ignition. By replacing the resistive cable and resistor of the aftermarket ignition with a non-resistive cable and surface discharge igniter, its ignition delay was reduced to 7 ms, which is comparable to that produced by the non-thermal ignitions.

Nomenclature

AFRL	=	Air Force Research Laboratory, located at the Wright-Patterson Air Force Base
CJ	=	Chapmann-Jouget
DDT	=	deflagration-to-detonation time; equal to detonation time minus ignition delay
Detonation Time	=	time from the ignition spark to initiation of a detonation wave
Exciter	=	high voltage ignition circuit consisting of capacitors, diodes, resistors, and switches
FWHM	=	full width at half the maximum height
Igniter	=	a spark-plug or device that produces electrical discharges; can also be an ignition system

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Ignition Delay	=	time from the ignition pulse to a pressure rise due to heat release
J	=	Joule
MSD	=	Multiple Spark Discharge Ignition, an aftermarket automotive ignition
nF	=	nano-farad
PDE	=	pulsed detonation engine
pF	=	pico-farad
pps	=	pulses per second
TE	=	Transverse Exciter, a 100-ns ignition built at the Air Force Research Laboratory
TPI	=	Transient Plasma Ignition, a 100-ns ignition built at The University of Southern California
WPAFB	=	Wright-Patterson Air Force Base, located in Dayton, OH
Φ	=	fuel-air equivalence ratio

I. Introduction

Pulse detonation engines are being developed because of their mechanical simplicity and potential to operate efficiently at high speed. The basic constraint on PDE engine operating frequency is the time to fill, ignite, detonate, and purge each thrust tube. In the PDE engine under test, the ignition delays are much larger than the deflagration-to-detonation (DDT) times. Thus, an ignition system that can minimize the ignition delay over fuel-air equivalence ratios of 0.8 to 1 is highly desirable to increase PDE operating frequency and thrust, while reducing engine size.

Ignition systems that produce 100-ns electrical discharges have been shown to reduce the ignition delay below that obtainable with standard spark ignitions.[1] These ignitions are often referred to as pulsed corona, fast transient, transient plasma, non-equilibrium or non-thermal ignitions in the literature. A 100-ns electrical discharge is the initial breakdown phase of an arc, but here the discharge is terminated before its impedance collapses. Fast transient discharges produce streamers of highly reactive radicals and excited molecules which accelerate the ignition process.

Fast transient ignition has been shown to reduce the ignition time on other PDE engines.[2] Ignition with non-equilibrium electrical ignitions is under investigation by other research groups on a variety of propulsion systems, including PDE engines. [3,4,5,6,7,8] For example, Starikovskii et al[9] have proposed an array of fast-ionization discharges to reduce ignition delays in PDE engines.

The tests described below are a subset of an initial survey to compare the capabilities of thermal and non-thermal ignitions in a PDE engine over a variety of operating conditions. The engine is fueled with aviation gasoline. A more complete description of the tests is given elsewhere.[10]

II. Experimental Setup

A. Pulsed Detonation Engine

A schematic of the AFRL pulsed detonation engine located at Wright-Patterson AFB, OH is shown in Fig. 1. Compressed air and aviation gasoline were premixed and preheated to 370-480 K, then injected through a General Motors Quad 4 engine head and into two 5.2 cm internal diameter, 1.85 m long thrust tubes where it was ignited and then detonated. The fill volume of the fuel-air mixture within the thrust tubes was regulated by the fuel-air manifold pressure, the camshaft/valve timing in the engine head and the repetition rate. The fuel-air mixture filled approximately 100% of the thrust tubes before ignition. The valve timing was 120° each for the fill, fire, and purge cycles. The repetition rate was 10 pps. With aviation gasoline as the fuel, two thrust tubes were operated 180° out of phase to provide consistent fills. A Shchelkin spiral was installed inside one thrust tube to aid in detonation, whereas the second tube has no spiral. Only the tube with the spiral was ignited with a spark plug, corona igniter or surface discharge igniter; the detonated fuel was directed out the open end of the tube to the atmosphere, generating thrust. The fuel-air mixture in the second thrust tube (without the spiral) was not ignited with a spark plug, but flowed out the open end where it was ignited by the exhaust from the first tube. To monitor the progression of detonation waves, a series of the ionization probes were installed along the first thrust tube, as shown in Fig.2. The ionization probes were spark plugs with the center electrode charged to low voltage. An electrical discharge through the spark plug is an indication of plasma. Detonation wave fronts are weakly ionized and, thus, can be recorded by ionization probes as they propagate down the thrust tube.

Two important measurements are reduced from data recorded by a digital acquisition system: the ignition delay, which is the time from when the ignition system fires to when a pressure increase due to heat release is observed in the thrust tube, and the detonation time, which is the time from when the ignition system fires to when a detonation wave is first observed. A detonation wave is said to occur when the wave speed becomes 90% of the theoretical CJ

velocity of ~1800 m/s. From these two measurements, the deflagration-to-detonation time (DDT), which is equal to the detonation time minus the ignition delay, is calculated.

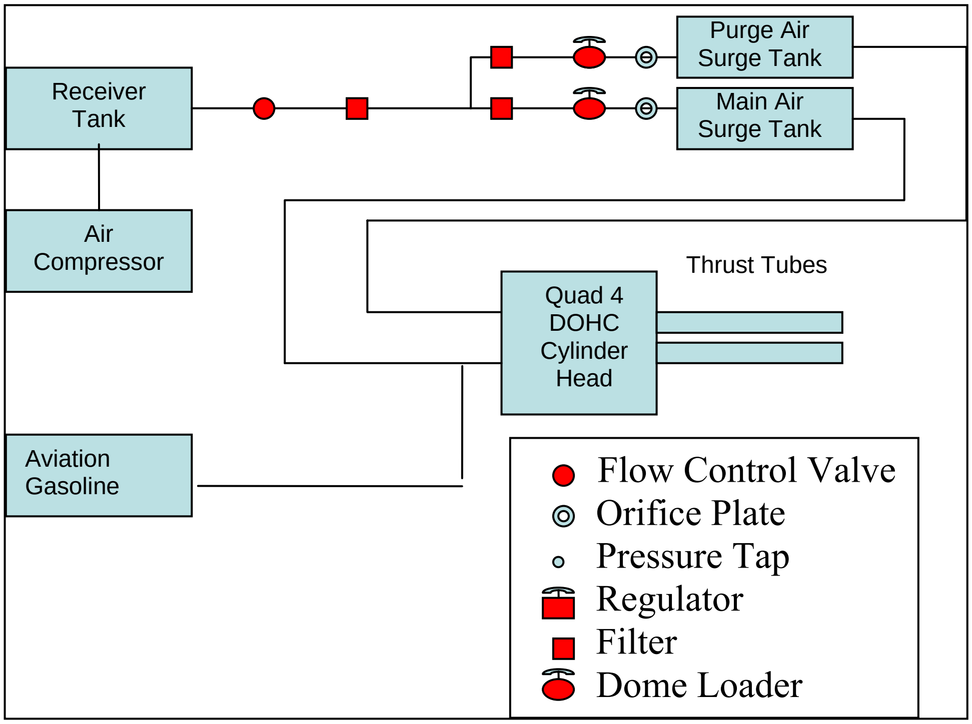

Figure 1. Pulsed Detonation Engine Configuration

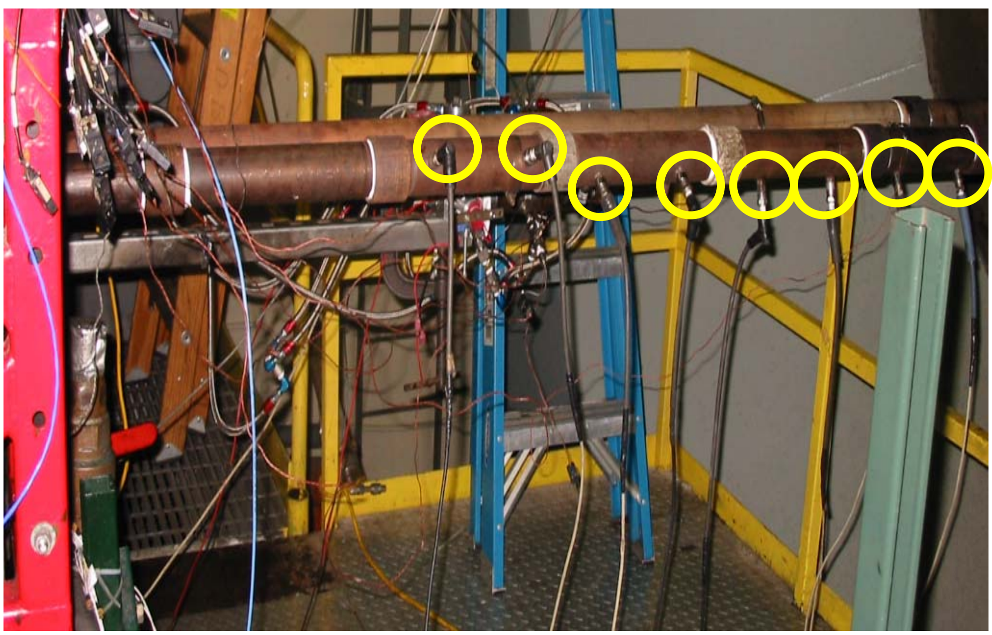

Figure 2. The location of ionization probes (highlighted by the yellow circles) along a thrust tube.

B. Exciters

Five different ignition systems were compared in these tests: the Transverse Exciter (TE), the Transient Plasma Ignition (TPI), the AFRL ignition, the Multi-Spark Discharge (MSD) ignition, and a modified MSD ignition. The TE, TPI and AFRL ignitions are non-thermal in nature, whereas the MSD and modified MSD ignitions are thermal ignitions. The ignitions allow comparisons based on the type of discharge (thermal and non-thermal), type of igniter (corona igniter, surface discharge igniter, or spark plug), polarity, and energy.

The TE ignition is a 100-ns, capacitive discharge ignition built at the AFRL. It is so named because its primary application is to inject electrical pulses transverse to high speed airflow in scramjet combustors. The TE ignition is a new system and was included here to test its reliability before progressing onto high speed air tunnel tests. Typical output pulse voltages are 25 to 40 kV. The TE ignition circuit can be arranged to produce either positive or negative pulses to test ignition capability of both polarities. TE ignition energy is adjusted by varying the exciter capacitance. The discharge generally begins with a corona like discharge and terminates in a spark. The efficiency of energy transfer from the exciter to the electrical discharge is 25 to 45% with surface discharge igniters, depending on discharge length, and about 45% with corona igniters. Circuit design and operation are described elsewhere.[11]

The TPI ignition, built at the University of Southern California, is a capacitive discharge ignition consisting of a lumped element Blumlein and a 3:1 step-up transformer to produce high voltage output pulses, typically 52 to 66 kV peak with a full-width, half-maximum (FWHM) duration of 50 to 75 ns. The discharge is a corona discharge that fills a 2.5 to 5 cm long section of the thrust tube. Efficiency of energy transfer from the exciter to the electrical discharge is typically 50%. Exciter energy is varied by adjusting the charging voltage. In these tests, the TPI exciter was operated only in positive polarity with a corona igniter, although it can operate with negative polarity also. A description of the TPI ignition is provided in Ref. 2.

The AFRL ignition is a negative output pulse version of the TE igniter with the output switch removed. In this setup, the exciter capacitance and the high voltage electrode of the igniter are directly connected. The charging time is from 0.5 to 10 milliseconds (depending on capacitance) and, when the maximum hold-off voltage of the igniter is exceeded, a 100-ns discharge from the high voltage electrode of the igniter to ground occurs. Data from this ignition is not included in this paper, although the best results are comparable with those reported here.

The MSD ignition is an aftermarket automotive spark ignition, part number 6215. It is a multi-channel, programmable, capacitive-discharge ignition with a resistive cable and spark plug. The voltage rises to a peak of 6.5 kV (the spark gap breakdown voltage) in about 5 μs, and, after breakdown, the ignition produces a peak current of 0.4 A. The FWHM of the power pulse is about 1 μs, with the current pulse continuing for about 50 μs thereafter. The current is limited by the resistance of the cable and the spark plug. The exciter energy is 0.105 to 0.115 J. The efficiency of energy transfer from the exciter to the electrical discharge is about 3%. All baseline measurements are done with this ignition. This ignition is also referred to as the unmodified MSD ignition.

The improved MSD ignition is the MSD exciter, with the resistive cable and spark plug replaced by a non-resistive cable and a surface discharge igniter, thus increasing the energy delivered to the electrical discharge.

C. Igniters

Three types of igniters are used in the tests: a corona igniter, a surface discharge igniter, and a spark plug. Schematics of the corona and surface discharge igniters are shown in Figs. 3 and 4. All igniters are mounted in the PDE engine head and centered in the cylindrical thrust tube. The gray areas are metallic flanges or pipes, the white areas enclosed by thin black lines are voltage-insulating ceramics, the thick black lines are wires or threaded rods, and the red areas are electrical discharges. All the figures have cylindrical geometry. The corona and surface igniters are made from the same device, consisting of a threaded 0.32 cm diameter metallic electrode, a 0.95 cm diameter ceramic tube surrounding the electrode, and a metallic fitting that screwed into the PDE engine head. With the corona igniter, the ceramic is pushed approximately 10 cm into the combustion chamber so that a radial electrical discharge forms between the high voltage electrode to the grounded thrust tube. The radial distance between the high voltage electrode and the grounded thrust tube is approximately 2.6 cm and, thus, a peak voltage of about 30-66 kV is required to form an electrical discharge. The TE and TPI ignitions were used with the corona igniter. With the surface igniter, the ceramic tube length is adjusted between 1 and 20 mm such that the electrical discharge forms along the surface of the ceramic, from the high voltage electrode to the grounded engine head. A peak voltage of 20 to 40 kV is required to form the electrical discharge. The TE and modified MSD ignitions were used with the surface discharge igniter. The spark plug is a modified AC Delco 41-629, or equivalent. The spark plug has a 1.1 cm outer diameter, 0.88 cm long metallic cylinder welded onto the end, with two vent holes located 180° from each other. This modified spark plug is used exclusively with the unmodified MSD exciter.

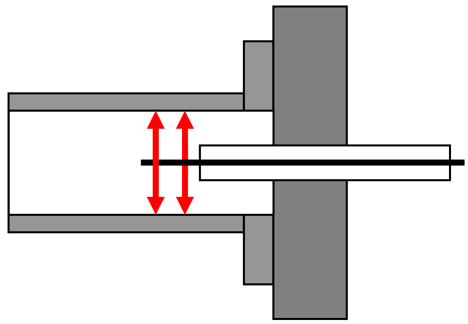

Figure 3. Placement and Operation of Corona Igniter in a PDE Thrust Tube

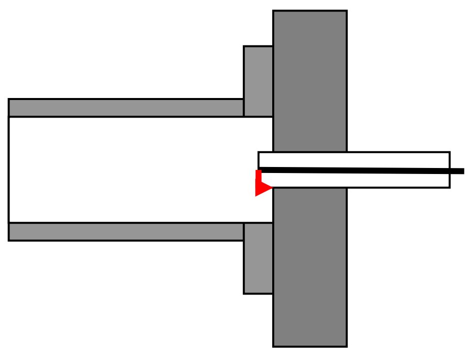

Figure 4. Placement and Operation of a Surface Discharge Igniter within a PDE Thrust Tube

III. Experimental Results

The baseline ignition delays and deflagration-to-detonation times as a function of fuel-air equivalence ratio (φ) are shown in Fig. 5. This data was taken with the unmodified MSD ignition with a modified spark plug operated in the PDE fueled by aviation gasoline. Data was recorded over a fuel-air equivalence range of 0.8 to 1.2. The ignition delay is 9.5 ms at $\varphi = 1.2$, rising to 11 ms at $\varphi = 1$ and 16.5 ms at $\varphi = 0.8$. The DDT times remain approximately constant near 2 ms. The curves are second order polynomial fits to the data recorded at $\varphi = 0.8$, 1, and 1.2. These curves are included in the following graphs for comparison.

Ignition delay and DDT data for a TE ignition that produces positive polarity pulses and the modified MSD ignition are shown in Fig. 6. A surface discharge igniter (shown in Fig. 4) is used with both ignitions. The PDE is fueled with aviation gasoline. Each data point (at each equivalence ratio) represents an average of 1 to 6 measurements. Data scatter is typically ±2 ms. The curves are based on a second degree polynomial fit to the data

points. The energy levels quoted in the figures are estimated exciter energies. Neither the charging voltage nor the output voltage and current waveforms of the exciter were monitored during operation. All the TE ignition delay curves lie below the baseline MSD ignition delay curve. As the capacitance and energy increases, the ignition delay decreases, while the DDT times remain approximately constant. The shortest ignition delays are 6.5 ms at $\varphi = 1$ and 1.2 and 11 ms at $\varphi = 0.8$ when a 4 nF capacitor is installed in the TE exciter. The spread from the lowest capacitance (130 pF) to the highest capacitance (4nF) is 1.5 ms at $\varphi = 1$ and 1.2 and 5 ms at $\varphi = 0.8$.

A comparison between the TE ignition delays at two selected capacitances and the modified and unmodified MSD ignition delays are shown in Table 1. Note that the modified MSD ignition delays are comparable to those of the TE ignition, although the exciter energy of the modified MSD ignition is less. The data indicate that a thermal (modified MSD) ignition can produce ignition delays comparable to those of a non-thermal (TE) ignition, under the present PDE operating conditions of 1 atmosphere pressure and 360 to 480 K. By replacing a resistive cable and spark plug with a non-resistive cable and surface discharge igniter, the ignition delay produced by a MSD ignition system can be reduced by 4 ms at lean and stoichiometric fuel-air ratios.

Table 1. Comparison of TE, Improved MSD, and Unmodified MSD Ignition Delays

Fuel-Air Equivalence Ratio	0.8	1.0	1.2
TE Ignition, Surface Discharge Igniter. 650 pF, 0.25 J	12 ms	7 ms	7 ms
TE Ignition, Surface Discharge Igniter, 4 nF, 1.5 J	11 ms	6.5 ms	6.5 ms
Improved MSD Ignition, Surface Discharge Igniter, 0.115 J	12.5 ms	7 ms	8.5 ms
Unmodified MSD Ignition, Modified Resistor Spark Plug, 0.115 J	16.5 ms	11 ms	9.5 ms

A similar set of data for a TE ignition that produces negative polarity pulses is shown in Fig. 7. In this case, a corona igniter is used (shown in Fig. 3). The shortest ignition delays were produced with the largest capacitance, 1.3 nF, except at $\varphi = 1.2$ where the 237.5 pF capacitance produced slightly better results. Comparisons of the ignition delays produced by positive and negative pulses at two selected capacitances are shown in Tables 2 and 3. For the case of a 237.5 pF capacitance, the ignition delays at $\varphi = 1$ and 1.2 are about 7 ms for both polarities, whereas the ignition delay for the positive polarity is 3.5 ms longer. In the case of a 1.3 nF capacitance, the ignition delays were nearly the same at each of the fuel-air equivalence ratios (11 ms at $\varphi = 0.8$ and 7 ms at $\varphi = 1.0$ and 1.2). The data indicates that the negative polarity, corona igniter setup has an advantage over the positive polarity, surface discharge igniter at low energy and capacitance (237.5 pF). At the higher capacitance (1.3 nF), the difference in ignition delays between a positive pulse with a surface discharge igniter and a negative pulse with a corona igniter are small.

Table 2. Comparison of TE Ignition Delays with a 237.5 pF Capacitance

Fuel-Air Equivalence Ratio	0.8	1.0	1.2
Fig. 6 – Positive Polarity, Surface Discharge Igniter	14.5 ms	7 ms	7 ms
Fig. 7 – Negative Polarity, Corona Igniter	11 ms	7.5 ms	7 ms

Table 3. Comparison of TE Ignition Delays with a 1.3 nF Capacitance

Fuel-Air Equivalence Ratio	0.8	1.0	1.2
Fig. 6 - Positive Polarity, Surface Discharge Igniter	11 ms	7 ms	7 ms
Fig. 7 – Negative Polarity, Corona Igniter	10.5 ms	7 ms	7 ms

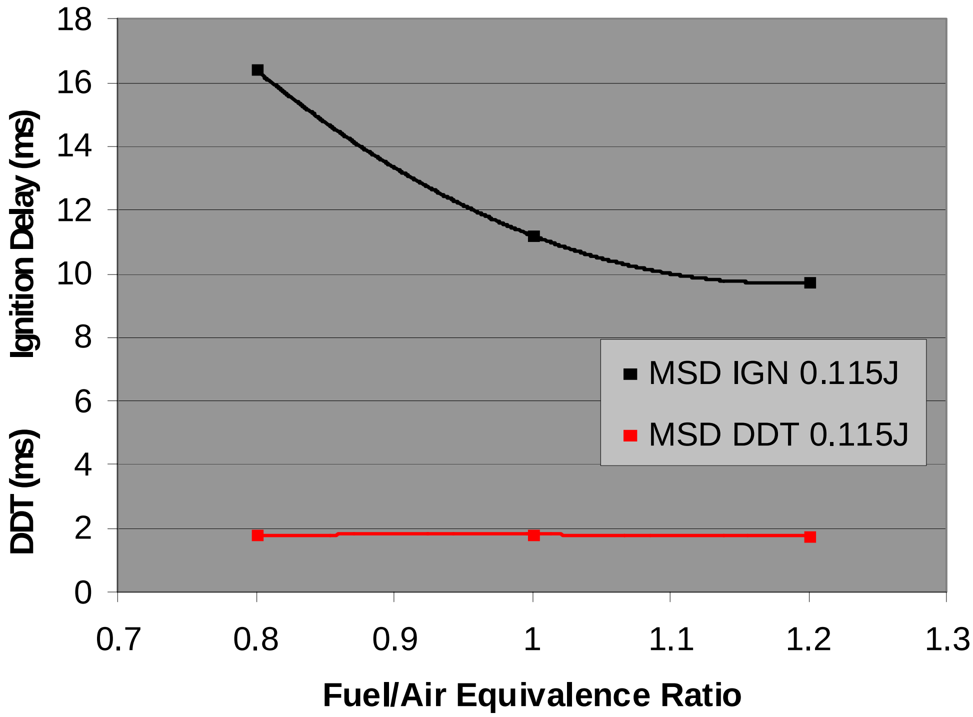

Figure 5. Baseline Ignition Delays and DDT Times with Aviation Gasoline

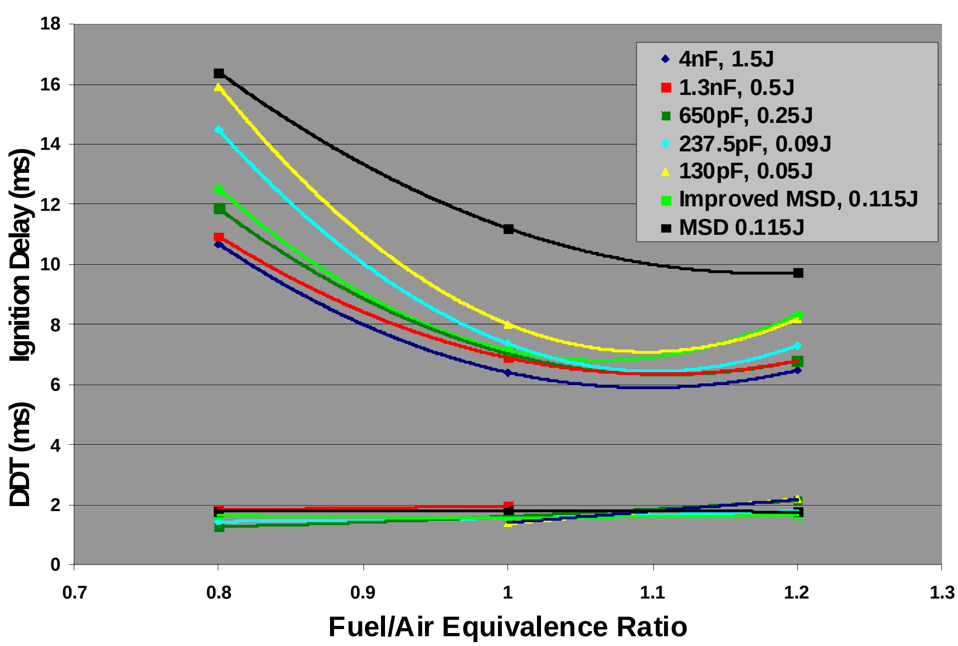

Figure 6. Ignition Delays and DDT Times for the Positive Polarity TE Ignition and the Modified MSD Ignition with a Surface Discharge Igniter

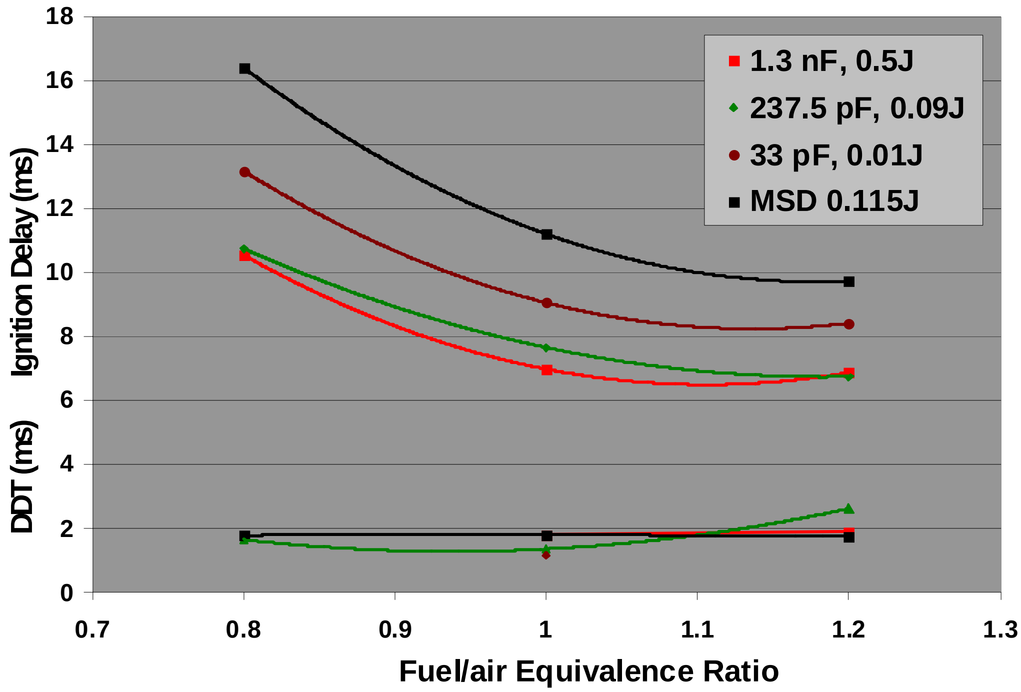

Figure 7. Ignition Delays and DDT Times for the Negative Polarity TE Ignition with a Corona Igniter

The ignition delays and DDT times produced by the TPI Ignition with a corona igniter are shown in Fig. 8. The ignition delays produced by the TPI ignition are less than those produced by the unmodified MSD ignition. The TPI ignition produces 52 to 66 KV pulses that over-stressed the ceramics of the corona igniter, producing undesired corona discharges that reduced the energy available for ignition. The length of the discharge volume was determined by the length of threaded rod exposed at the end of the igniter. The length was 2.5 to 5 cm. In Fig. 8, the lowest ignition delays are produced when the TPI exciter energy is 3.4 J, except at $\varphi = 1.2$ where the 2.2 J setting produced slightly better results. The ignition delays for the 3.4 J setting are 11 ms at $\varphi = 0.8$, 6 ms at $\varphi = 1.0$, and 5.5 ms at $\varphi = 1.2$. These ignition delays are equal to or slightly better than the ignition delays for the positive polarity 4 nF, 1.5 J TE igniter with a surface discharge igniter in Fig. 6 (11 ms at $\varphi = 0.8$, 6.5 ms at $\varphi = 1.0$, and 6.5 ms at $\varphi = 1.2$). The ignition delays for φ between 0.8 and 1.0 are most important because it is desirable for the PDE to operate under lean conditions to conserve fuel. The DDT times appear to increase for the TPI when the exciter energy is 3.4 J. A similar trend was observed with hydrogen as the fuel (which is not presented in this paper).

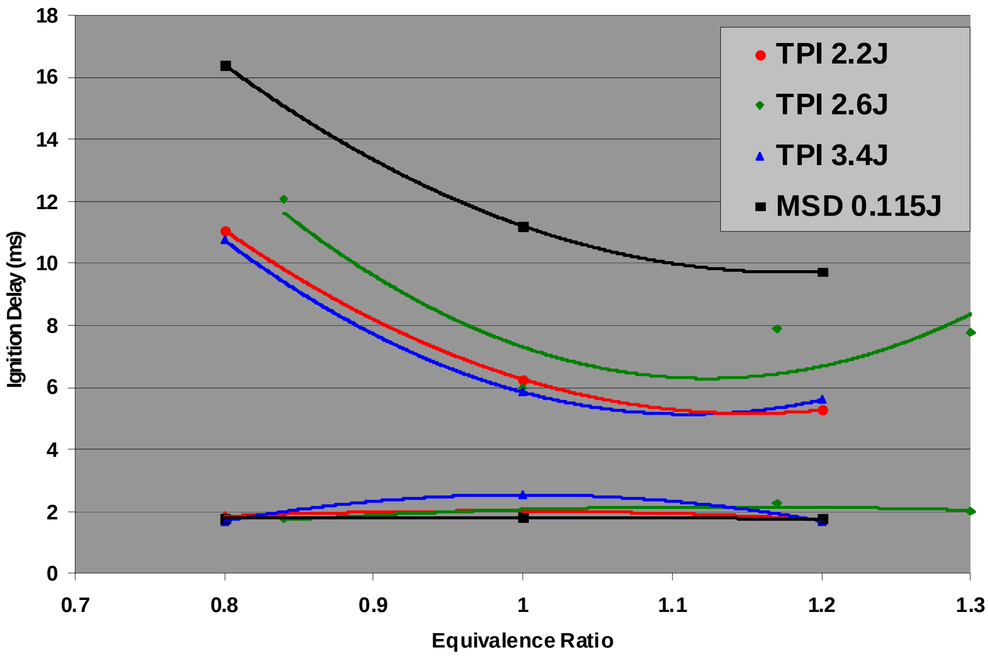

Figure 8. Ignition Delays and DDT Times for the Positive Polarity TPI Ignition with a Corona Igniter

IV. Conclusion

In a preliminary survey on an experimental pulsed detonation engine fueled with aviation gasoline, it has been demonstrated that non-thermal ignitions can reduce the ignition delay by 5-6 ms, or equivalently 30 to 45%, below that observed with an aftermarket automotive ignition at lean to stoichiometric fuel-air equivalence ratios. Non-thermal ignitions with 0.5 to 3 J energies produce the shortest ignition delays. Ignition delays are approximately the same for positive corona or negative spark discharges. It has also been demonstrated that by a simple modification of an aftermarket automotive thermal ignition, ignition delays can be reduced by 4 ms under the same PDE operating conditions, but with 0.115 J exciter energy. The shortest ignition delay at $\varphi = 1$ was 6 ms, produced by the Transient Plasma Ignition. At $\varphi = 0.8$, an ignition delay of 11 ms was observed with both the Transverse Exciter and the Transient Plasma Ignition. Ignition delays were substantially longer than the deflagration-to-detonation times, which were about 1 to 3 ms.

Acknowledgments

Distribution Statement A; Approved for public release; distribution is unlimited.

This effort was performed under contract number F49620-02-C-0015 with the AFOSR.

This research was performed while K.O. Busby held a National Research Associateship Award at Wright-Patterson AFB.

The authors gratefully acknowledge the technical assistance of Curt Rice, Royce Bradley and Kevin Kirkendall.

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